Modeling Phosphorous Loading for the Lake Eucha Basin

FINAL REPORT

EXECUTIVE SUMMARY

Submitted to:
Tulsa Metropolitan Utility Authority

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Introduction

Lake Eucha water quality is being degraded from excess algal growth. This excess growth is the result of an overabundance of nutrients in the lake, assumed to be primarily phosphorous. Most phosphorus in the lake comes from two sources, internal and external. The sediments in the lake itself release phosphorus to the water column, i.e. internal loading. Phosphorous coming into the lake from the watershed is external loading. External loading originates from either point-sources, such as the City of Decatur municipal waste water treatment plant, or from nonpoint sources like pastures. The majority of the phosphorous loading has been attributed to nonpoint sources.[1] Pastures in the Lake Eucha basin have received phosphorus from poultry litter applications for many years. Poultry litter is often applied to meet the crop's nitrogen requirements. When phosphorous in excess of what the crop can use is applied, phosphorous builds up in the soil. Runoff extracts soluble phosphorus from the soil and litter, and carries sediments containing phosphorous to the lake.

The SWAT (Soil and Water Assessment Tool)[2] model was used to predict how external loadings are affected by management changes. A range of soil test phosphorous levels and litter application rates were simulated. Long-term simulations project how soil test phosphorus likely changes over the next 30 years.

Results Summary

Observed data were used to estimate phosphorous loads in the basin and to calibrate the SWAT model. A variety of Best Management Practice (BMP) scenarios were evaluated through SWAT model simulations. The effects of soil test phosphorous, litter application rates, cattle grazing rates, and the City of Decatur point source were each evaluated through model simulations. The stochastic variability associated with rainfall was quantified, and used to estimate confidence intervals. The following is a summary of the findings from this study:

- The observed average total phosphorous loading to Lake Eucha is estimated to be 47,600 kg per year.

- Some areas contribute a disproportionate amount of phosphorous.

- The City of Decatur wastewater treatment plant accounts for approximately 24% of the estimated total phosphorous load to Lake Eucha.

- Anthropogenic nonpoint sources account for 73% of the total phosphorous loading to Lake Eucha.

- Eastern portions of the basin have a higher pasture soil test phosphorous.

1

Wagner, K., Woodruff, S., "Phase I Clean Lakes Project, Diagnostic and Feasibility Study of Lake Eucha", Oklahoma Conservation Commission, 1997.

2

Arnold, J.G., R. Srinivasin, R.S. Muttiah, and J. R. Williams. 1998. Large Area Hydrologic Modeling and Assessment: Part I. Model Development. JAWRA 34(1):73-89.

- Phosphorous load per unit pasture area, as estimated from monitoring data, is higher in the eastern portion of the basin.

- The SWAT model predicts a positive correlation between phosphorous loading to Lake Eucha and poultry litter application rate.

- The SWAT model predicts that increases in STP will result in increased loading to Lake Eucha.

- Dramatic increases in soil test phosphorous are predicted by the SWAT model with continued application of poultry litter.

- There are some discrepancies with phosphorous loadings between our estimates and the 1997 Phase 1 Oklahoma Conservation Commission study.

Results

Loadings

Observed water quality data collected by the City of Tulsa and stream flow records from the U.S. Geographic Survey (USGS) were used to estimate nitrate and phosphorous loads in the Lake Eucha basin. Load estimates for the period August 1998 to April 2000 were used to calibrate the SWAT model. In addition, these loads were compared with those calculated by the Oklahoma Conservation Commission in 1997 for the period March 1993 to February 1994 (Figure 1, Table 1). The 1997 Oklahoma Conservation Commission study reported that Beaty Creek contributed a disproportionate phosphorous load for its size. Our estimates of phosphorous load vary significantly with the OCC estimates for Beaty Creek and Spavinaw Creek. This discrepancy is likely the period of record used to calculate nutrient loading. Our estimates are likely more accurate, since we were able to use more data.

External loading to Lake Eucha has three sources; point sources, anthropogenic non-point source, and background. Figure 2 contains a breakdown of nitrate and total phosphorous by source. Background loading was estimated using the SWAT model by assuming the entire basin was forest, and using the hydrologic calibration from Black Hollow. Background total phosphorous and nitrate were estimated to be 1,440 and 113,000 kg/yr, respectively. Monitoring data from November 1997 to August 2000 show the average annual total phosphorous and nitrate loading from point sources to be11,600 kg/year and 5,440 kg/yr, respectively. The Decatur municipal waste water treatment plant was the only significant point source identified.

Table 2 shows phosphorous loading per unit area at each City of Tulsa water quality station. The location of each water quality station is given in Figure 3. GIS landcover data were used to estimate the fraction of pasture and forest in the contributing area at each water quality station. Forested areas were assumed to contribute 0.05 kg P/ha/yr. Higher phosphorous loading per unit pasture area are estimated in the eastern portions of the basin at stations EUC08, EUC09, EUC10, and EUC11. SPAV06 also indicates a high loading per unit pasture area. However, because there is only a small fraction of pasture in this area, it is very sensitive to loading estimates of forested areas.

Relationships between nutrient concentration and flow were developed for ten water quality stations using the available nutrient data. Using three flow gages, daily flow was estimated at ungaged stations using flow from the closest gaged station and assuming flow was proportional to drainage area. Gaging records ranged from approximately two to ten years and high flow nutrient data were limited. The uncertainty of these relationships can be very high where the gaging record is short because the record typically lacks the full range of flow from low to high flow events.

Nutrient loads were estimated for each station by applying the concentration-flow relationships to daily flow data from August 1998 through April 2000. This period of record was selected because it is the period in which flow data were available for all stations and quality assurance protocols for nutrient data were implemented. It should be noted that the nutrient component of the SWAT model was calibrated using these loading estimates.

Table 1 Total phosphorous and nitrate loadings to Lake Eucha estimated from monitoring data for the period August 1998 to April 2000, and March 1993 to February 1994 by subbasin compared to Oklahoma Conservation Commission study[1] for the period March 1993 to February 1994. A similar subbasin configuration was used for both loading estimates (Figure 1).

	Estimates for period (8-98 to 4-00)		Estimates for period (3-93 to 2-94)		OCC study (3-93 to 2-94)	
SITE	Total P (kg/yr)	Nitrate (kg/yr)	Total P (kg/yr)	Nitrate (kg/yr)	Total P (kg/yr)	Nitrate (kg/yr)
Rattlesnake	329	10,000	267	9,440	324	7,640
Brush	3,700	28,300	2,370	39,100	1,570	39,100
Beaty	6,620	117,000	6,080	162,000	11,600	157,000
Dry	404	16,100	605	24,200	1,040	24,800
Spavinaw	33,700	486,000	35,100	797,000	13,700	549,000
Eucha Laterals	2,840	21,800	1,820	30,000		
Misc. area					1,570	39,100
Entire basin	47,600	680,000	46,200	1,060,000	29,800	816,000

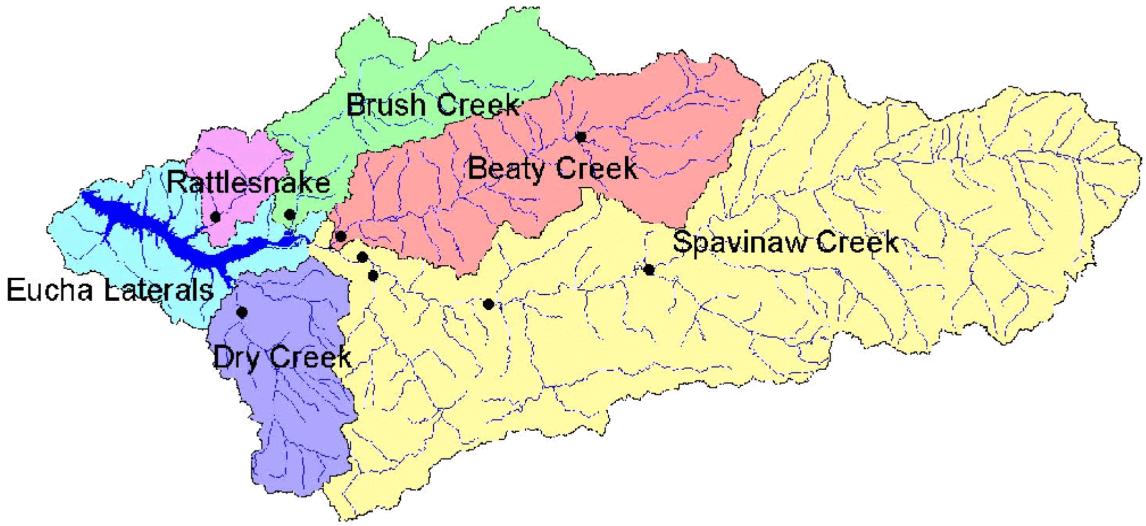

Figure 1 Lake Eucha subbasin layout used to calculate nutrient loads in Table 1. Dots indicate City of Tulsa water quality stations.

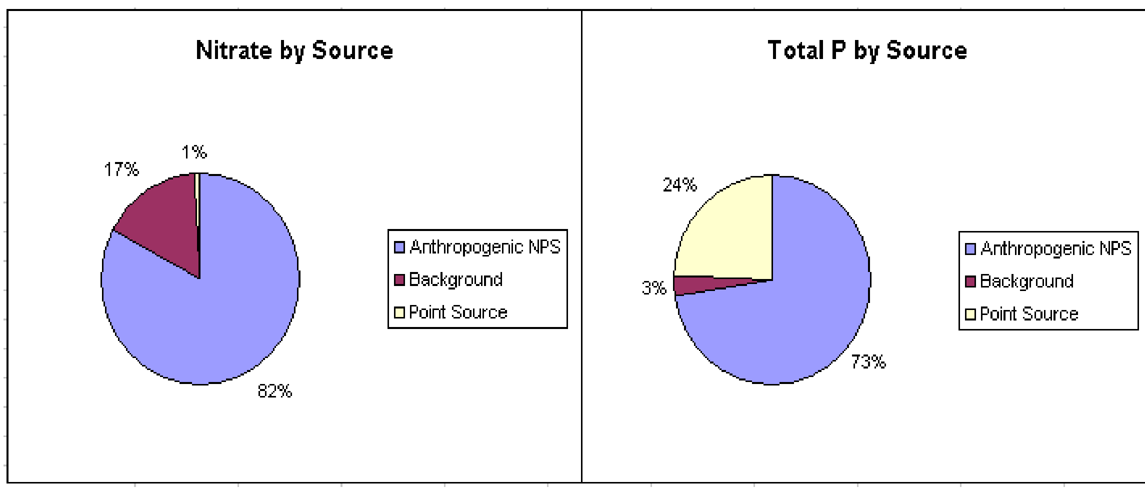

Figure 2 Lake Eucha total phosphorous and nitrate loading by source. Point source loading based on monitoring data from November 1997 to August 2000. Background Nonpoint Source (NPS) loading based on SWAT simulations of Lake Eucha basin as all forest. Anthropogenic NPS loading estimated by difference compared to observed loading.

Table 2 Estimated Lake Eucha observed phosphorous loading per unit pasture area in the contributing area above each water quality station. Forests are assumed to contribute 0.05 kg P/ha/yr.

Tributary	SITE	Total Area (km^2)	Pasture Area (km^2)	Forest Area (km^2)	Total P (kg/yr)	Estimated Total P from Forest (kg/yr)	Total P from Pastures (kg/ha/yr)
Rattlesnake Creek	EUC04	20.9	5.4	15.5	295	78	0.40
Brush Creek	EUC05	87.0	43.1	43.9	3,610	220	0.79
Beaty Creek	EUC06	153.0	89.9	62.9	6,550	315	0.69
Dry Creek	EUC07	50.6	15.5	35.1	283	175	0.07
Spavinaw Creek	EUC08	517	253	264	33,300	1,320	1.26
Spavinaw Creek	EUC09	424	216	207	40,900	1,040	1.84
Spavinaw Creek	EUC10	269	152	117	15,800	586	1.00
Beaty Creek	EUC11	65.9	47.3	18.6	7,580	93	1.58
Cloud Creek	EUC12	64.3	27.5	36.8	712	184	0.19
Black Hollow	SPAV06	15.6	0.8	14.9	173	74	1.32
Total		1,670	851	816	109,000	4,080	
						Average	0.92

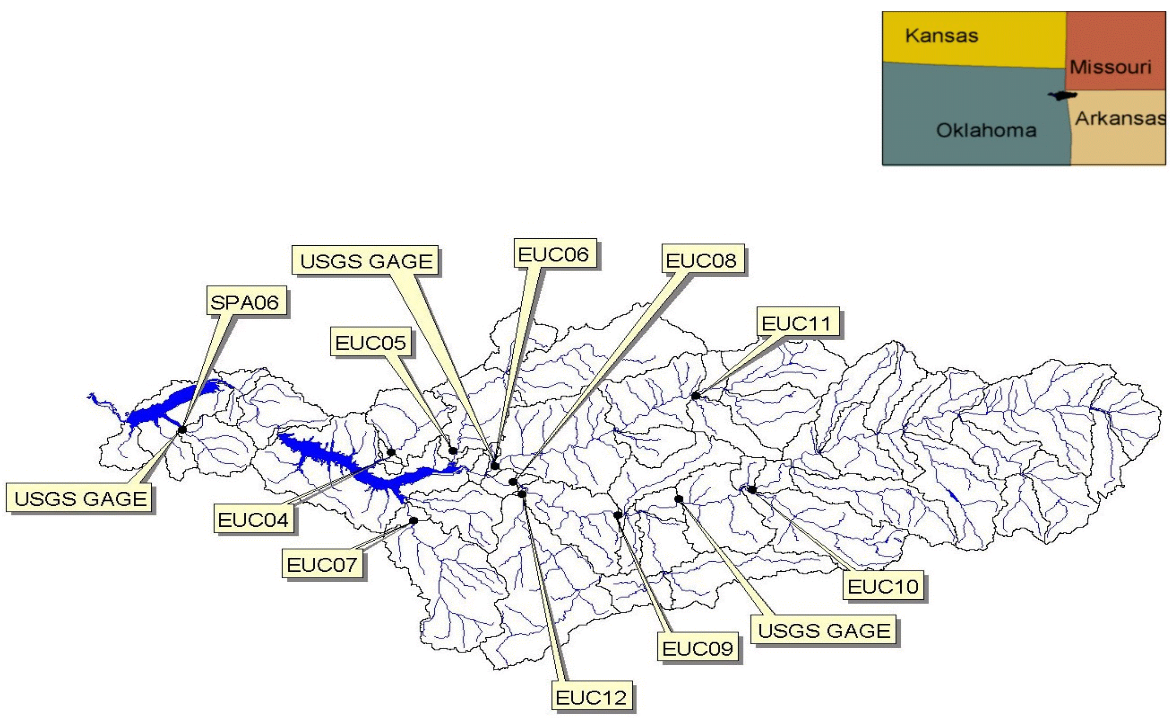

Figure 3 City of Tulsa water quality stations and USGS stream flow gage locations for the Lake Eucha and Lake Spavinaw basin.

Management and STP

The current application rate of poultry litter was calculated from the number of animals located in each subbasin (Figure 4). All litter generated in a subbasin was assumed to be applied in that subbasin. Because field specific data were not available, a cattle grazing operation was assumed for all pastures in the basin.

Marshall (1998)[3] developed a nonparametric method to determine the number of samples required, within a 90% confidence interval, to estimate subbasin soil test phosphorous by land use for hydrologic/water quality modeling. This method was applied to the Eucha Basin, and a soil sampling plan was developed for pastures and forested areas. The Oklahoma Conservation Commission was contracted to collect these soil samples for the Oklahoma portion of the basin. A summary of the soil test data is given in Figure 5

For the Arkansas portion of the basin, soil test phosphorous data for the period 1994 to 1997 were obtained from the Arkansas Soil and Water Conservation Commission for Benton County (Figure 6). Observed soil test phosphorous for pastures was used in the SWAT model. Forested areas use a SWAT model based estimate, based on simulations of an undisturbed forested watershed in north-central Arkansas. A summary of the STP data used in the SWAT model is given in Figure 7.

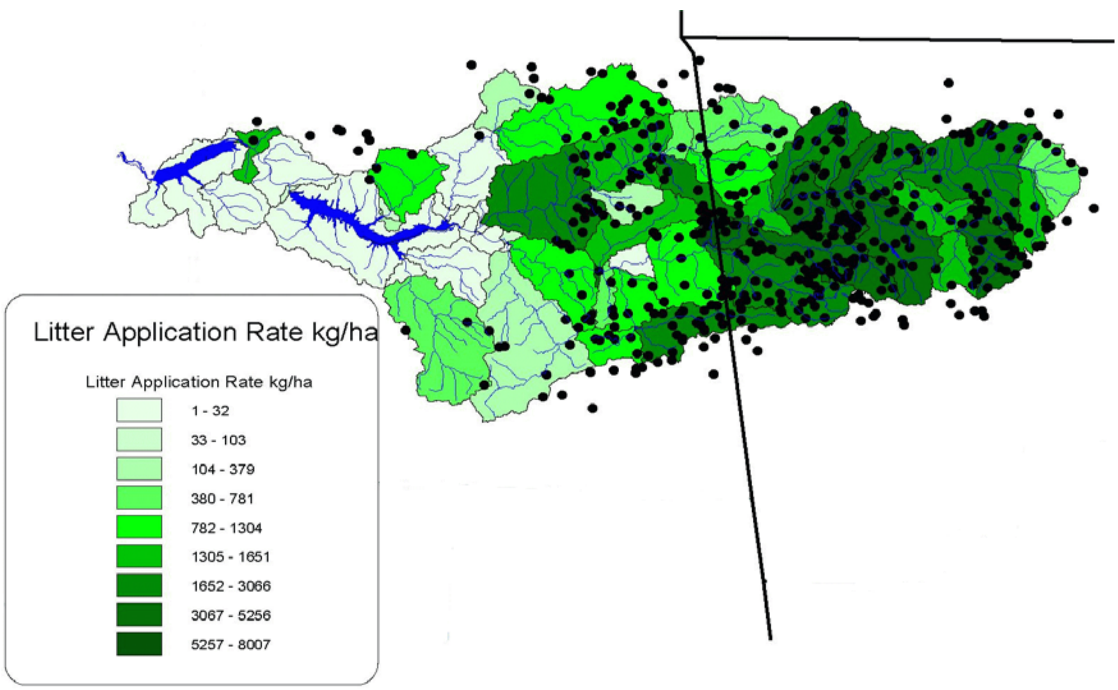

Figure 4 Lake Eucha and Lake Spavinaw poultry litter application rate by subbasin used in the SWAT model and poultry house locations (black dots).

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3 Marshall, W., “A Nonparametric Approach to Determine the Number of Observations Required for Estimating Basin-Scale Soil Test Phosphorous.” Masters Thesis, Oklahoma State University, 1998

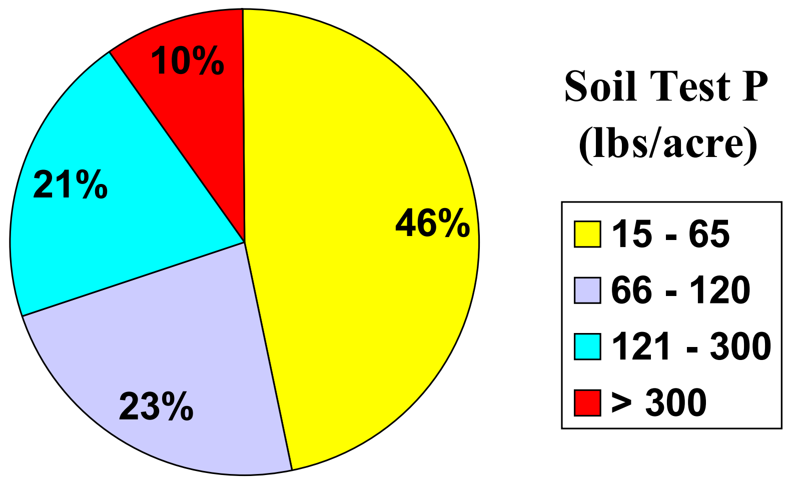

Figure 5 Soil test phosphorous summary for the Oklahoma portion of the Eucha/Spavinaw Basin. Soil samples collected by the Oklahoma Conservation Commission from August 1998 to May 1999.

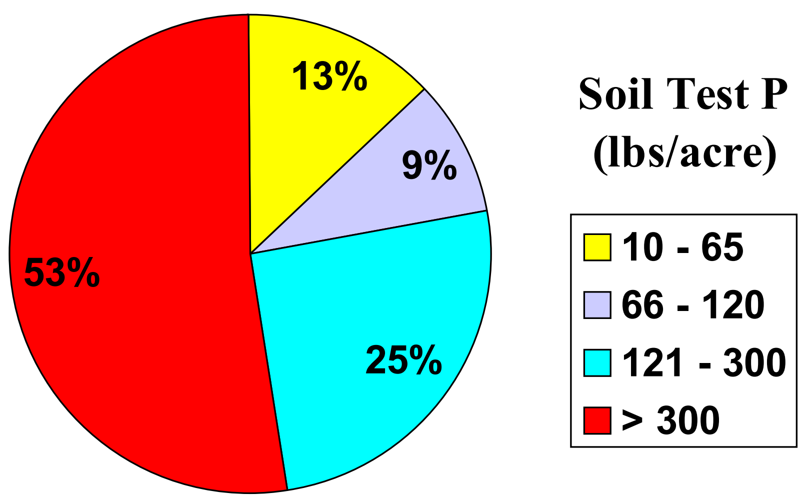

Figure 6 Soil test phosphorous summary for the Lake Eucha Basin, Benton County, Arkansas. Data provide by the Arkansas Soil and Water Conservation Commission, based on samples taken from 1994 to 1997.

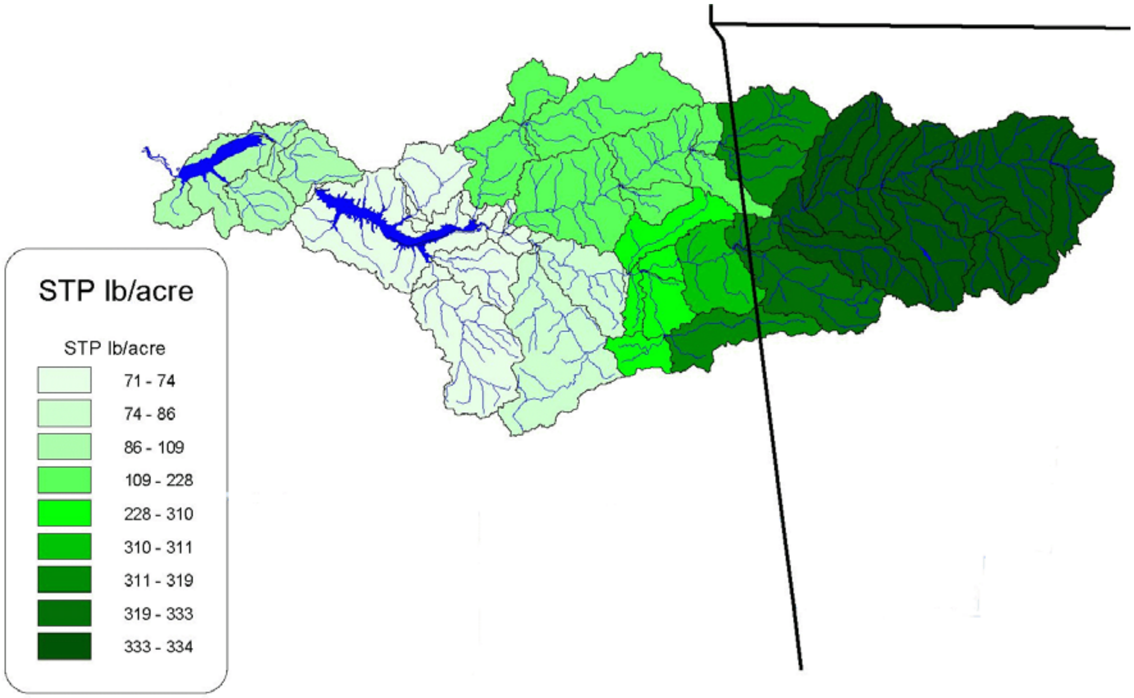

Figure 7 Average Lake Eucha and Lake Spavinaw Mehlich III soil test phosphorous (STP) for pastures by subbasin. Used in SWAT model simulations.

SWAT Model Calibration
GIS data for topography, soils, landcover, and streams were used in the SWAT model. The most current GIS data at the time of compilation were used. Observed daily rainfall and temperature data from 27 stations were utilized. The basin was broken into 58 subbasins based on topography, and further divided into combinations of soil and landcover called HRUs (Hydraulic Response Units). A total of 351 HRUs were utilized.

The SWAT model version 99.2 was calibrated using observed stream and nutrient data. Three USGS stream gage stations and ten City of Tulsa water quality stations were used in the calibration (Figure 3). Loadings were calculated at each station by developing a relationship between flow and observed nutrient concentration. Loadings were developed for soluble phosphorous, total phosphorous, and nitrate. The SWAT model was first calibrated on surface runoff and baseflow at each of the three gages. After hydrologic calibration, the model was calibrated for nutrients.

Stochastic Rainfall Simulations
The effect of soil test phosphorous, litter application, grazing, and point sources were each evaluated through SWAT model simulations. The stochastic uncertainty associated with rainfall was quantified by performing multiple simulations using differing periods in the observed rainfall record. Thirty simulations were performed to estimate confidence intervals.

Sediment-Bound Phosphorous Adjustments
Sediment-bound phosphorous was under predicted in all SWAT simulations (Table 3). We assume this is the result of phosphorous being deposited with sediment in the stream, but

not being re-entrained during high flow periods due to an error or limitation of the SWAT model. In addition, sediment that is re-entrained does not appear to contain phosphorous. To adjust for this, a correction factor was employed using the calibrated SWAT model and observed loadings. Sediment-bound phosphorous was underestimated by a factor of approximately 24 in the calibrated model. This fraction was assumed to be constant for all scenarios. Total phosphorous predictions calculated using this adjustment are labeled as (ADJ.).

Table 3 Observed and SWAT predicted loading to Lake Eucha. Predicted average annual refers to average loading of 30 years of stochastic rainfall simulations. (ADJ.) indicates sediment-bound phosphorous loading was adjusted.

Parameter	Observed 8-98 to 4-00	Predicted 8-98 to 4-00	Predicted 8-98 to 4-00 (ADJ.)	Predicted Average Annual	Predicted Average Annual (ADJ.)
Flow (m^3/sec)	9.80	9.80	9.80	9.13	9.13
Soluble P (kg/yr)	32,800	34,500	34,500	31,200	31,200
Sediment P (kg/yr)	14,800	613	14,712	665	15,960
Total P (kg/yr)	47,600	35,100	49,212	31,865	47,160
Nitrates (kg/yr)	680,000	644,000	644,000	507,000	507,000

Decatur Point Source

Based on monitoring data from November 1997 to August 2000, the total annual phosphorous point source loading from the City of Decatur was 11,600 kg/year (Table 4). On a long-term basis, almost all phosphorous entering the stream will eventually end up in the lake, providing there is no net long-term deposition of sediment or significant removal by wildlife. We performed SWAT simulations considering various levels of point source loading from the City of Decatur. However, these simulations have limited utility if you assume that all the phosphorous entering the stream reaches the lake.

Table 4 Current nutrient loading for the City of Decatur. Estimated from Permit Compliance System data from the Environmental Protection Agency for the period November 1997 to August 2000.

Parameter	Total P	Nitrates	Flow	Ammonia
Load	11,600 kg/yr	5,470 kg/yr	4,900 m^3/day	11,300 kg/yr
Concentration	6.53 mg/l	3.06 mg/l		6.33 mg/l

Litter Application Scenarios

The calibrated SWAT model was altered to depict nine different litter application/export scenarios. Litter application rates were adjusted by a fraction of the current estimated rate. An average of 0.77 ton/acre (1,747 kg/ha) were applied to pastures in the basin. All litter generated in a subbasin was assumed to be applied to pastures in that subbasin. In actuality, litter is moved between subbasins, into, and out of the Lake Eucha basin. However, data are not available to determine the actual application rate for each subbasin.

Predicted soluble and total phosphorous loading to Lake Eucha increased with increasing litter application (Figure 8). However, the effect of litter application is compounded by the effect of soil test phosphorous, since litter applications increase soil test phosphorous on a long-term basis. At reduced litter application rates, commercial nitrogen fertilizer was added to maintain a reasonable forage production. For this reason, the model predicted no significant reduction in nitrate loading at litter rates less than the current rate (Table 5).

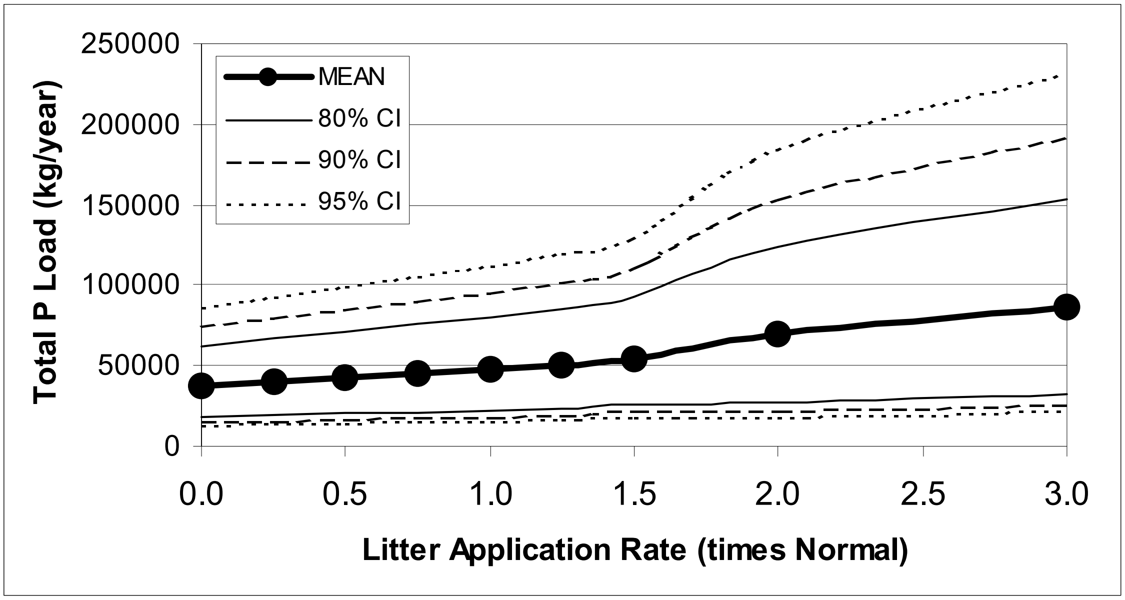

Figure 8 SWAT estimated total phosphorous loading to Lake Eucha as a function of litter application rate. Nitrogen is supplemented at rates less than the current poultry litter rate. Adjusted sediment-bound phosphorous used to calculate total phosphorous. Confidence intervals reflect only the variability associated with rainfall.

Table 5 Effect of litter application rate on the calibrated SWAT model. Adjusted sediment-bound P used to calculate Total P (ADJ.).

X Current Litter Application Rate	Flow (m^3/s)	Soluble P (kg/yr)	Sediment P (kg/yr)	Total P (kg/yr)	Total P (ADJ.) (kg/yr)	Nitrate (kg/yr)
0.00	9.13	22,500	630	23,100	37,600	508,000
0.25	9.13	24,600	640	25,200	40,000	508,000
0.50	9.13	26,900	649	27,500	42,500	508,000
0.75	9.13	29,000	660	29,700	44,900	507,000
1.00	9.13	31,200	665	31,900	47,100	507,000
1.25	9.23	34,800	657	35,500	50,500	598,000
1.50	9.31	38,300	680	39,000	54,600	688,000
2.00	9.42	44,800	1,040	45,800	69,600	866,000
3.00	9.51	56,600	1,230	57,800	86,000	1,180,000

Soil Test Phosphorous Scenarios

Simulations were performed at six levels of basin wide pasture soil test phosphorous ranging from 35 to 1000 lb phosphorous/acre. These six simulations were performed at three differing litter application rates, two are shown in Tables 6 and 7. At litter application rates less than current, nitrogen was supplemented to make up for the reduced nitrogen applied in litter. With increases in STP, SWAT predicts an increase in total phosphorous loading (Figure 9). STP had little or no effect on nitrates and water yield (Table 6).

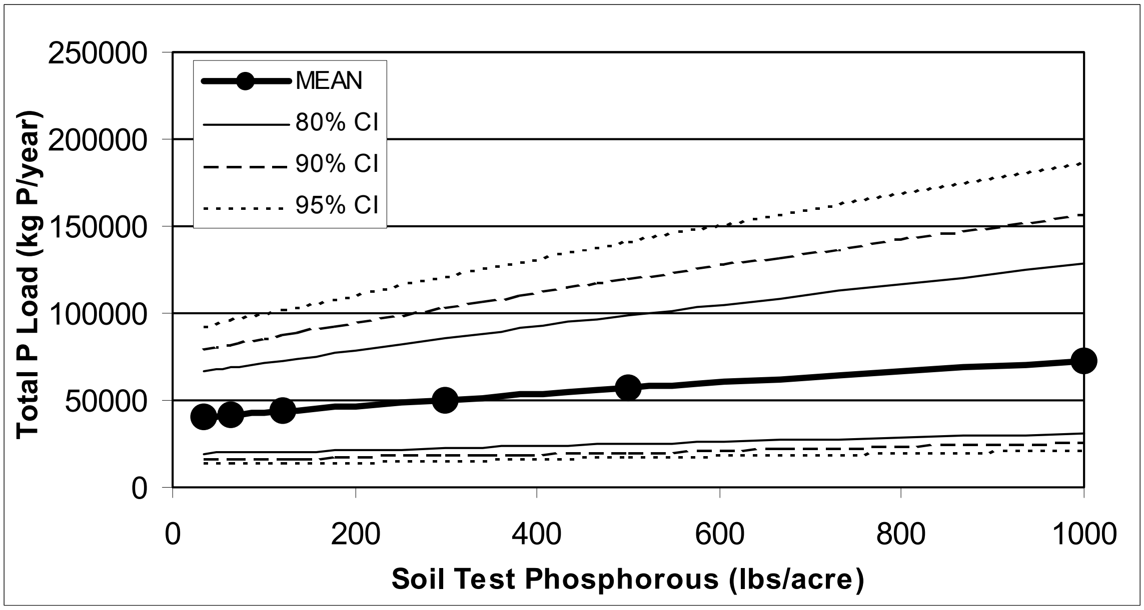

Figure 9 SWAT predicted total phosphorous loading to Lake Eucha at pasture soil test phosphorous ranging from 35 to 1000 lb/acre. Adjusted sediment-bound P used to calculate total P. Confidence intervals reflect only the variability associated with rainfall. These SWAT simulations used the current litter application rate.

Table 6 SWAT predicted mean annual loading to Lake Eucha at differing levels of pasture soil test phosphorous based on the current litter application rate. Adjusted sediment-bound P used to calculate total P (ADJ.).

Soil Test P (lb/acre)	Flow (m^3/s)	Soluble P (kg/yr)	Sediment P (kg/yr)	Total P (kg/yr)	Total P (ADJ.) (kg/yr)	Nitrate (kg/yr)
35	9.13	25,400	626	26,000	40,400	508,000
65	9.13	26,100	640	26,800	41,500	508,000
120	9.13	27,500	666	28,200	43,500	507,000
300	9.13	32,100	746	32,900	50,100	507,000
500	9.13	37,300	814	38,100	56,800	507,000
1000	9.13	50,000	946	50,900	72,700	506,000

Table 7 SWAT predicted mean annual loading to Lake Eucha at differing levels of pasture soil test phosphorous. No litter was applied, only commercial nitrogen. Total nitrogen applied is the same as the 1X litter application rate. Adjusted sediment-bound phosphorous used to calculate total phosphorous (ADJ.).

Soil Test P (lb/acre)	Flow (m^3/s)	Soluble P (kg/yr)	Sediment P (kg/yr)	Total P (kg/yr)	Total P (ADJ.) (kg/yr)	Nitrate (kg/yr)
35	9.13	16,800	576	17,400	30,600	509,000
65	9.13	17,500	593	18,100	31,800	509,000
120	9.13	18,900	622	19,500	33,800	509,000
300	9.13	23,500	711	24,200	40,600	508,000
500	9.13	28,600	785	29,400	47,400	508,000
1000	9.13	40,800	923	41,700	63,000	507,000

Long term simulations

Long term simulations were performed to estimate how average soil test phosphorous (STP) may change under different litter application rates. The current basin-wide STP for pastures was estimated at 250 lb/acre, based on actual soil test data. At the current litter application rate, the SWAT model predicted that the average pasture soil test phosphorous will increase by 50 lb/acre in 5 years and by 250 lb/acre in 24 years (Figure 10). A reduction of 18 lb/acre STP was predicted if no litter was applied for 30 years. The removal of phosphorus from the soil is dependant on management. For instance exporting hay from the basin will remove more phosphorous than grazing. The majority of the phosphorous consumed by cattle from grass is redeposited as manure. In addition, chemical reactions in the soil may alter the long-term STP as well.

To check the SWAT model, time required to build up STP based on SWAT simulations was compared with poultry production history in the area. The poultry industry came to Delaware County, Oklahoma about 25 years ago and about 40 years ago to Benton County, Arkansas (personal communication Jason Hollenback OSU Extension). At poultry litter application rates of 0.5 and 0.75 of the current rate, it would take 42 and 28 years for STP to increase from background to the current level of 250 lb/acre, respectively . Litter applications would have steadily increased from very little when there were few houses, to the current rate. Therefore, a fraction of the current rate between 0.5 and 0.75 is reasonable, and provides a reasonable verification of the method.

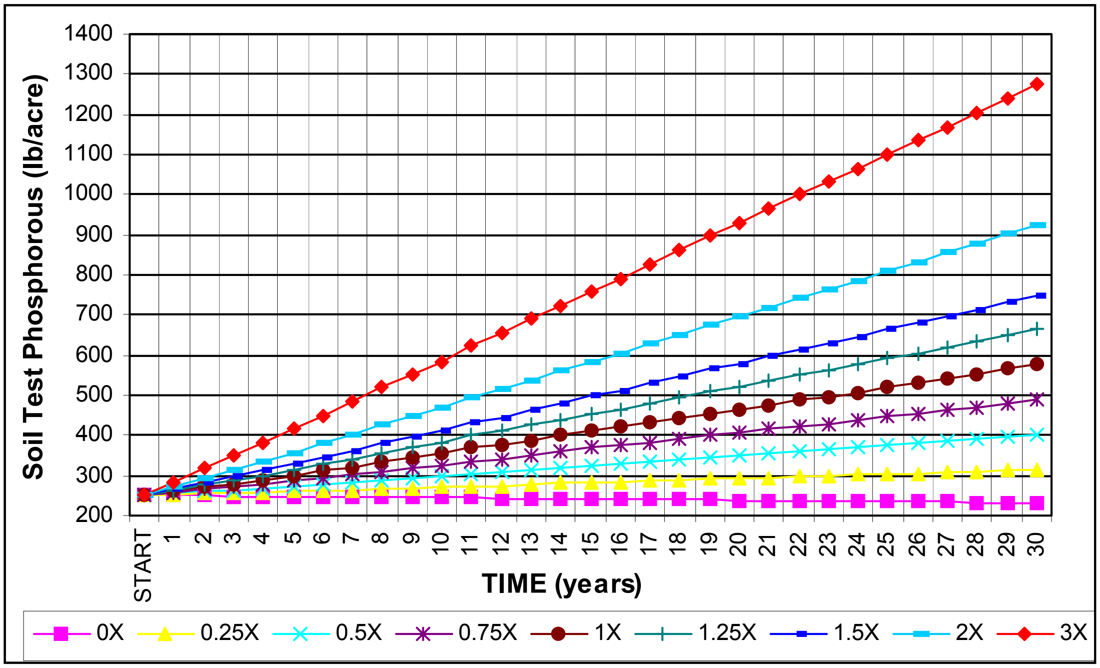

Figure 10 Predicted soil test phosphorous as a function of litter application rate (fraction of current rate) over a 30-year period for the Lake Eucha Basin.

SWAT Model Limitations

A model is a system of equations that represent a simplification of real world processes. The greater our understanding of these processes the better our models. Modeling requires many assumptions. Assumptions are made by the modeler, the model creator, and those who develop the relationships and define the process on which the model is based. There is a great deal of uncertainty associated with modeling. The nutrient loading for next year is every bit as unpredictable as next year's weather. We have quantified a portion of this uncertainty associated with rainfall variability. We know there are errors in the GIS data, water quality, and stream flow on which our calibration was based, but methods are currently not available to quantify the uncertainty from sources other than weather.[4]

Weather is the driving force for any hydrologic model. Great care was taken to include as much accurate observed weather data as possible. Unfortunately, weather data collected at a few points must be applied to the entire basin. Rainfall can be quite variable, especially in the spring when convective thunderstorms produce the majority of precipitation, and produce rainfall with a high degree of spatial variability.

An important limitation is that SWAT simulates poultry litter applications as simple nutrient additions applied uniformly to the top 10 mm of the soil surface. In reality poultry litter lies on the soil surface until rainfall moves it into the soil. In the first few rainfall events after

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Hession, W.C., D.E. Storm, "Watershed-Level Uncertainties: Implications for Phosphorous Management and Eutrophication" Journal of Environmental Quality" 29:1172-1179 (2000) application the litter interacts more closely with surface runoff than simulated by SWAT. In the field we expect high phosphorous concentrations in surface runoff immediately following litter application. In the SWAT model, simulated phosphorous concentrations do not increase so dramatically when litter is applied. These limitations caution us against using SWAT predictions on daily or even monthly basis. On an average annual basis, these loading errors are less pronounced due to calibration.

Another source of error was differences in soil test phosphorus (STP) data between Oklahoma and Arkansas. Oklahoma soil samples were analyzed by the Oklahoma State University (OSU) Soil, Water & Forage Analytical Laboratory and Arkansas soil samples were analyzed by the University of Arkansas (UA) Soil Testing and Research Laboratory. OSU and UA use extraction ratios of 1:10 and 1:7, respectively, and use different instrumentation for analysis. OSU uses a colorimetric method and UA uses inductively coupled argon plasma spectrometry (ICAP). Dr. Nathan Slaton with the UA provided the following relationships for different extraction ratios ($n \approx 500$):

$$\mathit{ICAP\,Mehlich\,III\,P}(1{:}10) = 1.27\ \mathit{ICAP\,Mehlich\,III\,P}(1{:}7) + 14.9$$

where Mehlich III is in mg/l. Dr. Hailin Zhang with OSU provided the following relationship between ICAP and the colorimetric method ($n=3577$, $R^2=0.98$):

$$\mathit{ICAP\,Mehlich\,III\,P}(1{:}10) = 1.11\ \mathit{Colormetic\,Mehlich\,III\,P}(1{:}10) + 26.7$$

where Mehlich III is in mg/l. The average pasture STP level used for the Arkansas portion of the Lake Eucha basin was 334 lbs/ac. Based on these regression equations, an Arkansas STP of 334 lbs/ac corresponds to an OSU value of 372 lbs/ac. In the context of this study, this 10 percent difference in STP is negligible.

Scenarios involving radical changes to the basin result in greater uncertainty. The model was calibrated using estimates of what is presently occurring in the basin. Large departures from calibration conditions raise the level of uncertainty.

SWAT models in-stream processes based, in large part, on unvalidated assumptions of channel and stream-bank properties. These in-stream processes are the primary cause of the low sediment-bound phosphorous prediction by the calibrated model.

Long-term simulations of soil test phosphorous assume SWAT`s soil phosphorous model is correct. The steady-state partitioning of phosphorous into SWAT`s various soil phosphorous pools was used to estimate soil test phosphorous. In reality this partitioning varies by soil type and cultural practices.